REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
6/1994

3. REPORT TYPE AND DATES COVERED
TECHNICAL

4. TITLE AND SUBTITLE
BOUNDARY CONDITIONS AND SOUND SCATTERING MODELS FOR VARIOUS ZOOPLANKTON

5. FUNDING NUMBERS
ONR N00014-89-J-1729
NSF OCE 9201264

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
WOODS HOLE OCEANOGRAPHIC INSTITUTION
WOODS HOLE, MA 02543

8. PERFORMING ORGANIZATION REPORT NUMBER
WHOI CONTR. 8655

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
OFFICE OF NAVAL RESEARCH
ENVIRONMENTAL SCIENCES
DIRECTORATE
ARLINGTON, VA 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
In citing this report in a bibliography, the reference given should be:
THIRD INTERNATIONAL CONGRESS ON AIR AND STRUCTURE-BORNE SOUND AND VIBRATION. JUNE 13-15, 1994, MONTREAL, CANADA, pp.1559 - 1562

12a. DISTRIBUTION / AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE:
DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS
1) SCATTERING
2) ACOUSTICS
3) ZOOPLANKTON

15. NUMBER OF PAGES
4

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED

20. LIMITATION OF ABSTRACT

THIRD INTERNATIONAL CONGRESS ON AIR- AND
STRUCTURE-BORNE SOUND AND VIBRATION
JUNE 13-15, 1994 MONTREAL, CANADA
pp. 1559-1562

BOUNDARY CONDITIONS AND SOUND SCATTERING MODELS FOR VARIOUS ZOOPLANKTON

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ABSTRACT

Echosounders are widely used in the remote detection and classification of marine organisms such as zooplankton. In order to interpret the data, accurate acoustic scattering models must be used. Zooplankton present a formidable challenge when attempting to describe their scattering properties. These animals come in many sizes, shapes, and material properties. The animals can be divided into several major categories of gross anatomical groupings – fluid-like or weak scatterers, bodies with gas-inclusions, and fluid-filled elastic shelled bodies. Approximate models according to the different shapes and boundary conditions have been developed for these anotomical types.

INTRODUCTION

There is a wide body of literature describing the scattering of sound by objects [1,2]. The work has almost exclusively involved simple objects such as spheres and infinitely long cylinders although there has been some work involving more complicated bodies such as prolate spheroids and finite cylinders. When attempting to describe the scattering of sound by zooplankton, the models involving idealized objects only have some utility in that they provide much intuition regarding the dominant scattering mechanisms. However, because of the great irregularity of the animals' boundaries and nonuniformity of their material properties, extensive research has been required in order to accurately describe the scattering by the animals. In particular, approximate models have been derived based, in part, on existing models involving idealized objects as well as laboratory scattering measurements [3-12].

SHAPE AND MATERIAL PROPERTY CONSIDERATIONS

The great challenge one has in modeling the scattering of sound by zooplankton is illustrated by the diversity of plankton (Fig. 1). The animals come in many sizes, shapes, and material properties. Because there are many thousands of species of the animals, it would be impossible to study the animals on a species by species basis. Hence, we have categorized the animals into several classes of gross anatomical features: fluid-like or weak scatterers, animals with gas inclusions, and fluid-filled elastic shelled animals. Furthermore, the shape has a profound effect on the scattering. Hence, another set of categories involves the shapes of spheres, finite length cylinders (straight and bent), and prolate spheroids. Our analyses to date have involved many combinations of both boundary condition and shape [3-12].

APPROXIMATE SCATTERING MODELS

We are investigating the scattering due to one realization of the animal (i.e. one echo for a given size, shape, and angle of orientation) as well as averages over those same parameters. The following summarizes research investigating the scattering due to a single realization of each type of animal which best illustrates the basic dominant scattering mechanisms. All results are given in terms of the scattering amplitude f, acoustic wavenumber k ($= 2\pi/\lambda$ where λ is the wavelength), and cylindrical or spherical radius a.

The krill (a shrimp-like animal) and salp both fall into the same category as being bent finite-length weakly scattering cylinders. The scattering has been shown, at least for the shrimp-like animals, to be dominated by contributions from echoes from the front and back interfaces of each body [10,11]:

$$f \simeq \tfrac{1}{2}\sqrt{\rho_c a}\,\mathcal{R}_{12}e^{-i2ka}(1 - T_{12}T_{21}e^{i4ka}e^{i\mu(ka)}) \quad , \qquad ka \gtrsim 0.1$$

where ρ_c is the radius of curvature of the cylinder axis, $\mathcal{R}_{12}$ is the reflection coefficient for the front interface, T_{12} and T_{21} are transmission coefficients, and μ is an empirically derived coefficient that extends the usefulness of this ray-based formula down to about $ka \sim 0.1$. The "1" term in the parentheses represents the echo from the front interface while the $T_{12}\ldots$ term corresponds to the back interface.

The siphonophore is mostly fluid-like but with at least one small gas inclusion near one end. Assuming that the gas dominates the scattering, the following simple approximate equation is used that describes the scattering by a single gas bubble [5,12]:

$$f \simeq \frac{a(ka)^2\alpha_{\pi s}G^{\frac{1}{2}}}{(1 + [4(ka)^4\alpha_{\pi s}^2]/(\mathcal{R}_{12}^2 F))^{\frac{1}{2}}} \quad , \qquad \text{all } ka$$

where $\alpha_{\pi s}$ is a term containing relative mass density and speed of sound, and G and F are empirically determined terms to describe the shape of the curve near resonance. Phase shifts were ignored in this all ka expression.

The gastropod (a small snail) is a fluid-filled elastic shelled body with an overall exterior that is more spherical than elongated (less than 2:1 ratio of length to width). To a first approximation, the animal is modeled as being a fluid-filled elastic shelled sphere. For this animal, data indicate that the scattering is dominated by the reflection from the front interface and the (subsonic) zero order (antisymmetric) Lamb wave. A simple ray-based equation that can be used to describe the scattering is [1]:

$$f \simeq \tfrac{1}{2}\mathcal{R}_{12}ae^{-i2ka} - \frac{\frac{1}{2}G_L a e^{-2(\pi-\theta_L)\beta_L}e^{i\eta_L}}{1 + e^{-2\pi\beta_L}e^{i2\pi kac/c_L}} \quad , \qquad ka \gg 1$$

where G_L is a coupling coefficient between the external field and the Lamb wave, θ_L is the "launching" angle of the Lamb wave, β_L is the attenuation coefficient of the wave, and c and c_L are the speeds of the external field and Lamb wave, respectively. The first term containing $\mathcal{R}_{12}$ represents reflection from the front interface (note that Ref. 1 contains a more general expression involving the thickness resonance). The second term containing G_L represents contributions from the many zero order Lamb waves that have circumnavigated the body 1,2,3... times.

CONCLUSIONS

Modeling the scattering of sound by zooplankton is a tremendous challenge due to their complex shapes and boundary conditions. Our laboratory data has provided much insight into what are the dominant scattering mechanisms for the different animals. Hence, we have been successful in describing the scattering by certain fluid-like, gas-bearing, and elastic shelled animals. Additional work is needed to extend these models to include other kinds of plankton.

ACKNOWLEDGEMENTS

The authors wish to thank Laurel Duda of the Woods Hole Oceanographic Institution for preparing this manuscript. This work was supported by the Ocean Acoustics and Oceanic Biology Programs of the Office of Naval Research grant number N00014-89-J-1729, and the Biological Oceanography Program of the National Science Foundation grant number OCE-9201264. This is Woods Hole Oceanographic Institution contribution number 8655.

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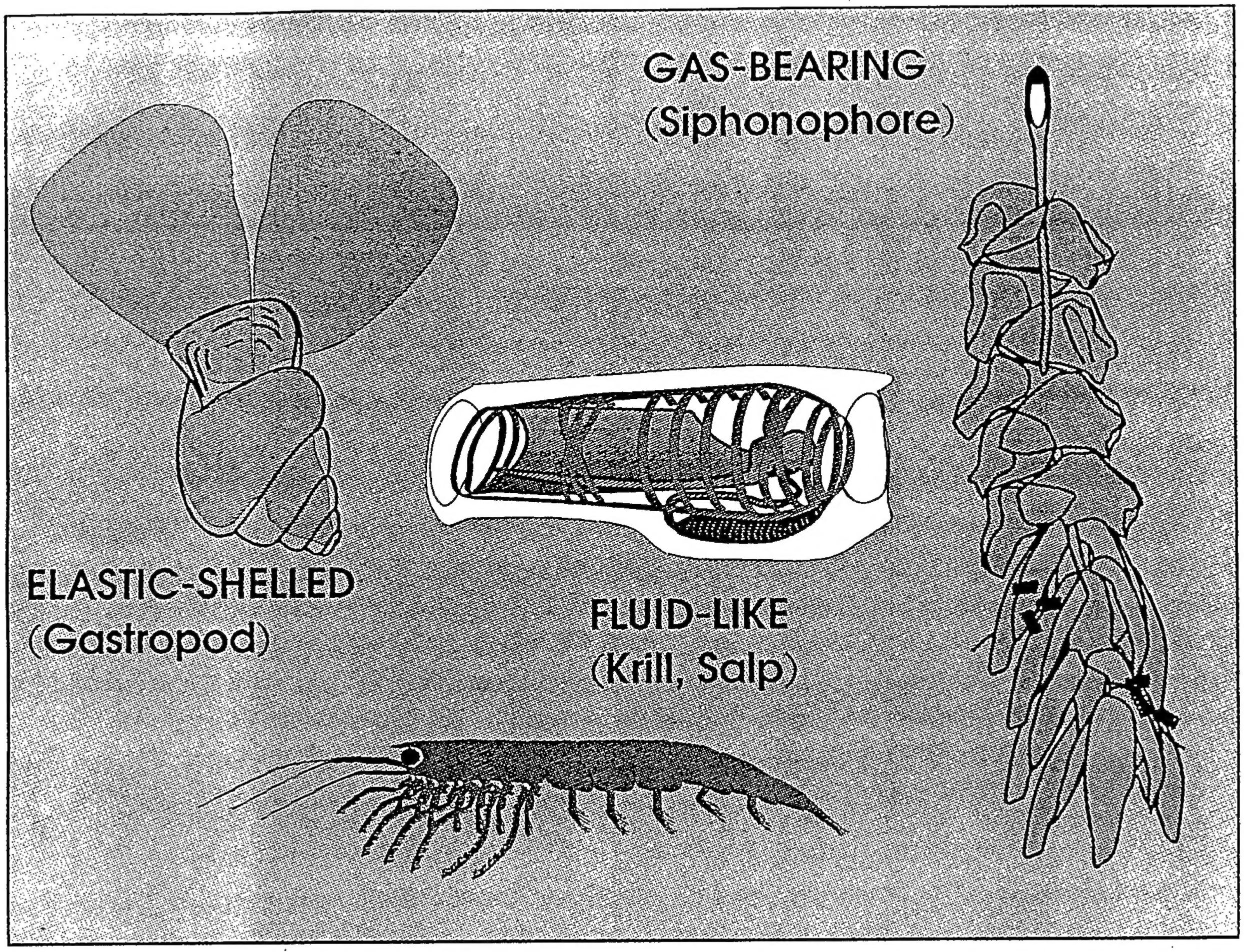

Figure 1. Various important zooplankton found in the sea. These fall into the major acoustic categories of fluid-like, fluid-filled elastic shell, and gas-bearing.